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Real-Time Monitoring of Pre-Collapse Phenomena Using Locations of Seismic Sources

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REAL-TIME MONITORING OF PRE-COLLAPSE PHENOMENA USING LOCATIONS OF SEISMIC SOURCES

by
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ABSTRACT

We attempted to develop a method for real-time monitoring of pre- collapse activity in the cavity region using seismic trace data recorded following EGMONT.

Signals from an array of eight three-component. short-period seismometer stations were recorded using a new high dynamic range. portable digital telemetry and recording system. Three stations were located at 1 DOB. three at 2 DOB. and two at 4 DOB. Seismic data were recorded continuously before. during. and after collapse.

As has been reported by previous studies. the pre-collapse period was characterized by a continuous high level of activity. but unlike previous studies. the recording system was not saturated. which allowed us to attempt to process the information. We discovered that all of the signals at a given location are very similar. but that the character is very different at the separate locations.

A variety of computer processing techniques were attempted with the aim of obtaining source locations accurately enough to monitor chimney growth. i.e.. $\pm$ 50m both horizontally and vertically. These included the traditional methods of picking arrival times of phases at the different stations and using the time differences to locate the source. as well as more unusual approaches. We concluded that an array of sensors such as that used for EGMONT will not produce satisfactory results with real-time processing.

We did. however. come up with an approach using several small. closely-spaced groups of sensors called arrays that should be more successful for this type of situation. The arrays. if designed properly. will take advantage of the similarity of the signals at a given location to estimate source direction. The directions from several arrays to one source can be combined to determine the source location.

INTRODUCTION

The purpose of this experiment was to test the feasibility of monitoring seismic signals from the cavity region between shot-time and collapse in order to track chimney growth and collapse activity. The analysis of the signals must be automated and in near real-time so that the activity can be quickly and accurately monitored for safety considerations.

Earlier studies by LANL (summarized by Edwards et. al., 1984) concluded that for most shots there were few or no locatable events in the pre-collapse period because the continuous level of activity was too high. A more recent study by Mills at LLNL using high dynamic-range digital recordings of the activity following the BRANCO event (Mills, oral communication, 1983) indicated that there may be locatable events in the pre-collapse period.

The initial goal of this project was to digitally record seismic signals generated after the EGMONT event and to use the data to develop algorithms for real-time processing. It was originally anticipated that this processing would consist of picking onset times of P- and S-waves from an array of three-component digital stations and locating events based on differences in the arrival times at the individual stations. It was hoped that some digital processing techniques could be employed to extract arrival time information from the 'noisy' data. In addition to the more traditional travel-time location methods described above, we planned to look at other digital processing techniques made possible by the high-quality data.

In order for the signal processing procedure to be useful for this application, it must be very robust, i.e., insensitive to changes in the character of the signals and the recording sites. Ideally, the system should work under a wide variety of conditions and require little site calibration before the shot or adjustments during the monitoring period.

EXPERIMENT DESCRIPTION

The seismic array consisted of eight three-component stations; six of these, which were located within 2 DOB of SGZ, used 4.5 Hz seismometers (TDC-1); the outer two stations were located at 4 DOB and used 1 Hz seismometers (S-13). The array configuration is shown in Figure 1. The seismometers were oriented with the radial component pointing towards SGZ and the transverse component perpendicular to the radial component.

The seismic signals were digitized at each site, and the digital signals telemetered to a central recording site located about 4.5 km from SGZ. Three hours of continuous trace data beginning at shot-time were recorded on a large magnetic disk. For a complete description of the digital telemetry and recording system, see LLNL UCRL 53608 (Nyholm, 1985).

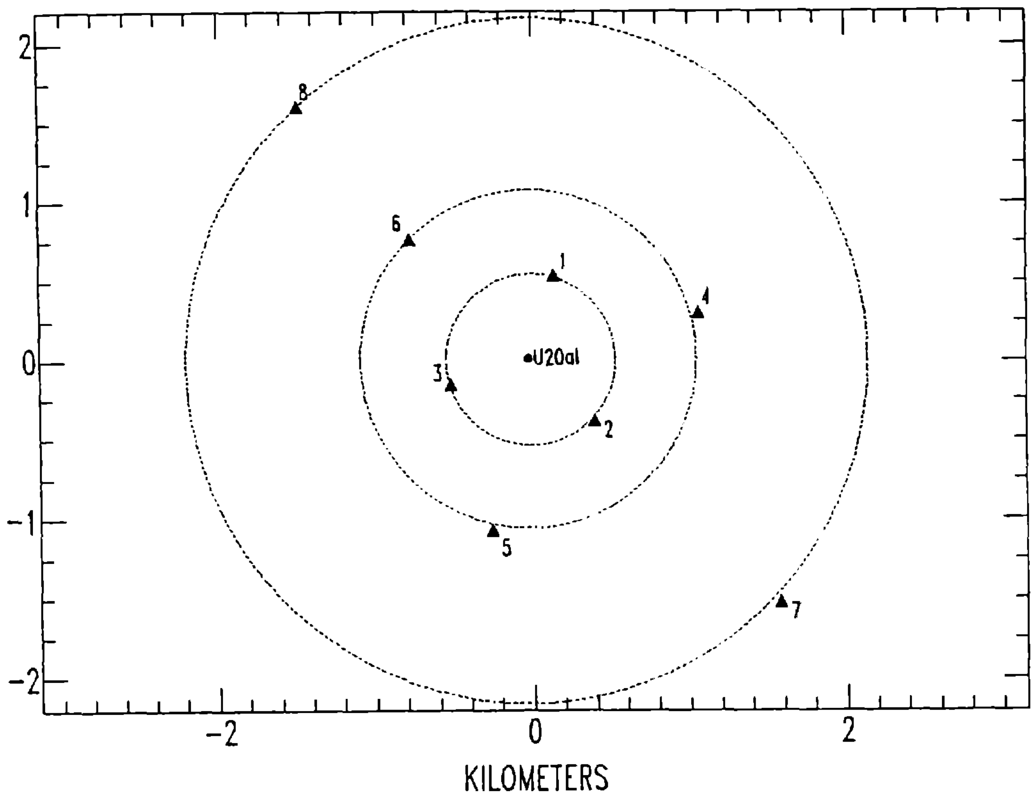

Figure 1. Station locations for the EGMONT seismic array. The inner circle is 1 DOB from SGZ, the middle circle 2 DOB, and the outer circle 4 DOB.

EXPERIMENT RESULTS

Due to a computer malfunction, the first 30 minutes of data were lost, but a continuous record was obtained from +30 min. to after collapse at about +42 min. This loss did not substantially affect the outcome of this study because the length of recording time was adequate to provide a detailed assessment of the nature of the problem. In addition to the pre-collapse data, over two hours of post-collapse activity was recorded.

Time series characteristics

Figure 2 is one trace starting at +30 min. and ending after collapse. The level of continuous activity is high compared to the pre-shot background (inset), and some distinct 'events' are visible. Figure 3 shows the radial trace from each station for a typical distinct event (denoted by the arrow in Figure 2) with the time scale expanded. All traces are plotted with the same vertical scale.

Some characteristics of the traces in Figure 3 worth noting are; the large variability between the individual stations and the lack of a clearly defined onset at most stations, due to the large amplitude preceding the onset of the signal and the emergent quality of

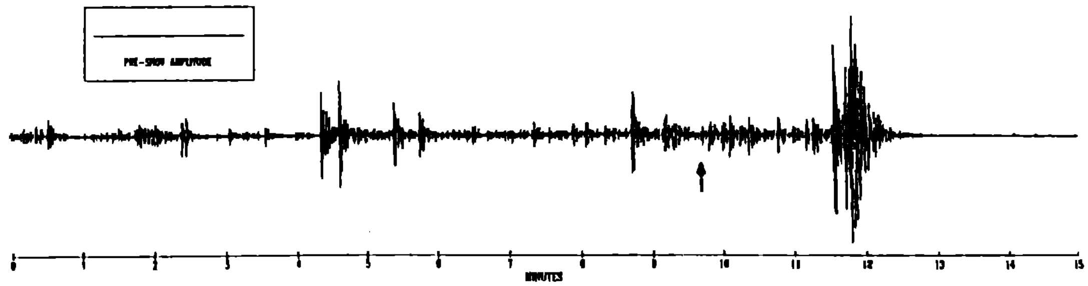

Figure 2. Continous record (station R08) from +30 minutes to +45 minutes, including collapse between 41 and 42 minutes. The inset is a seismogram recorded before the shot, plotted with the same vertical scale as the post-shot trace.

the onset. These characteristics are true in general for all of the pre-collapse events.

Spectral characteristics

Figure 4 shows a plot of the spectral characteristics of the traces in Figure 3. The time windows used are shown on Figure 3. The first window is the pre-event 'noise' (dotted in Figure 4) and the second window is the beginning of the 'signal' (solid in Figure 4). A high-resolution spectral estimator (Maximum Entropy Method) was used because of the short lengths of the data windows (1 sec.)

The spectra show large differences between the individual stations and very similar character of signal and noise at each station. This is important because many automatic processing algorithms utilize differences between signal and noise (both in the spectral and time domains) to identify phases and arrival times. The spectra of other events (see Figure 5 for an example) in the pre-collapse period showed that there were similarities between events at the individual stations, indicating that path effects are determining the spectral characteristics of the signals. The similar spectral character of 'signal' and 'noise' at the stations indicates that their paths are the same, so that their sources probably are near the same location.

Source characteristics

A general idea of the nature of the mechanism producing the seismic sources will be helpful in evaluating the approaches to our problem. It appears as if the high level of continuous activity is due to a superposition of many small sources, and the segments that

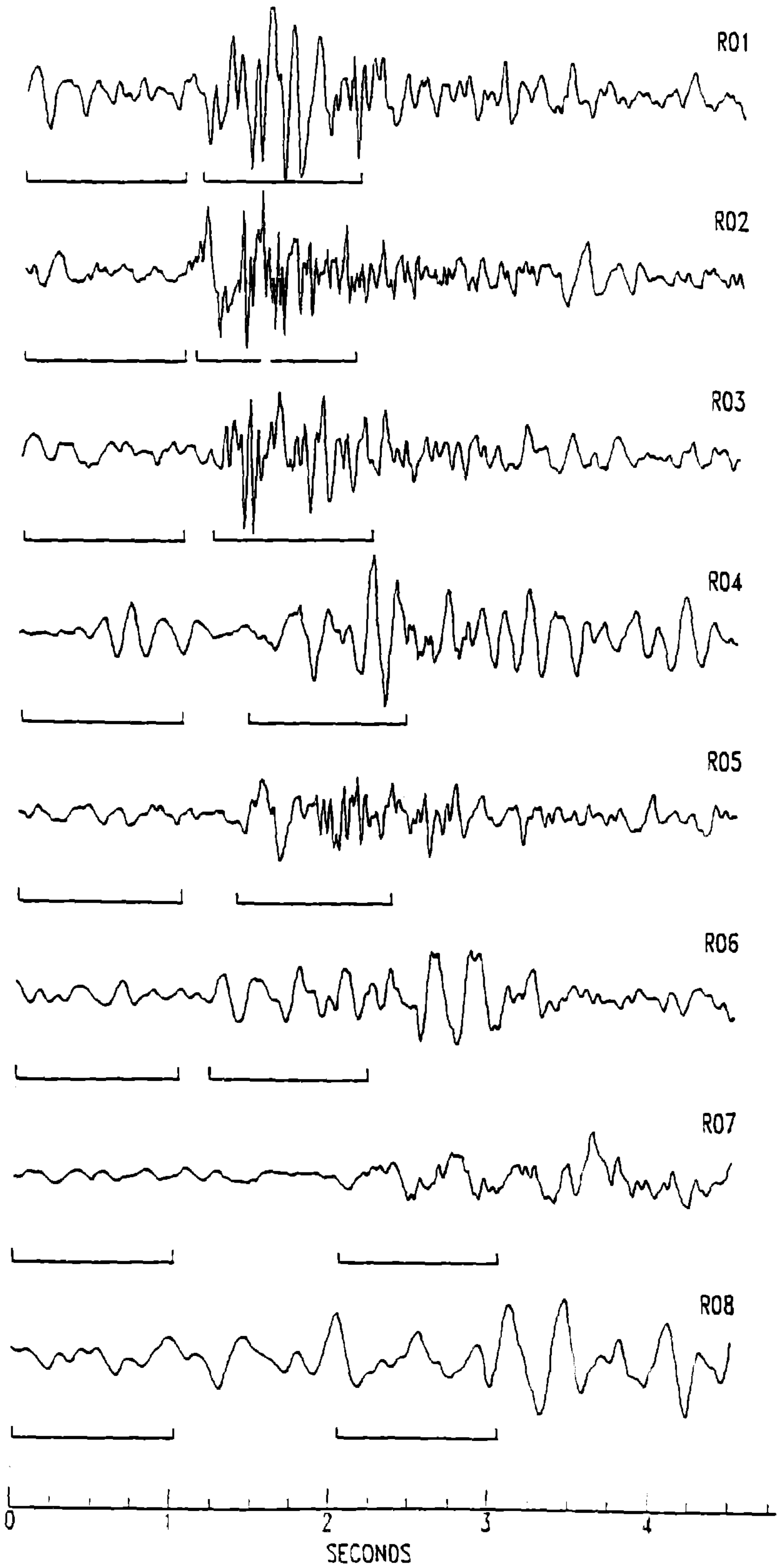

Figure 3. Five-second segments from the eight radial components for a typical event during the pre-collapse period. The first one-second window shown on each trace is used to compute the noise spectrum, and the second window is used to compute the signal spectrum for Figure 4.

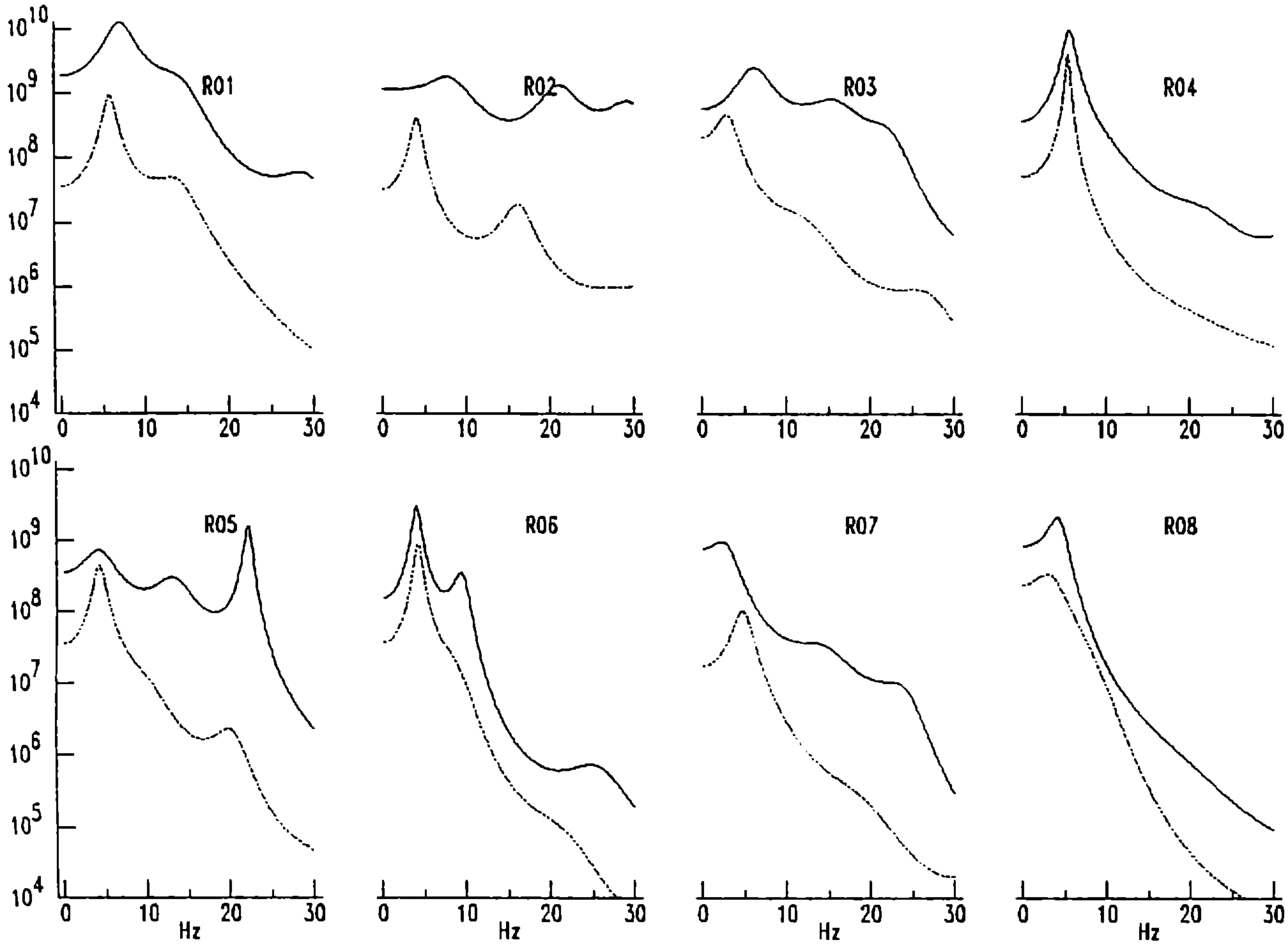

Figure 4. Power spectra for one-second segments of signal (solid) and noise (dotted) from the traces in Figure 3.

stand out are just larger versions of the same sources. Therefore, the difference between what we have been calling 'signal' and 'noise' is just that the signal is larger than the noise.

APPROACHES TO LOCATION PROBLEM

In order for the monitoring of seismic signals to be useful for tracking pre-collapse activity, the locations of the seismic sources must be known to within at least ± 50 m both horizontally and vertically. Traditional methods for locating seismic sources use the relative arrival times of P- and S-phases at the different stations to compute a location that best fits the arrival time information, assuming the velocity as a function of depth is known. Assuming a compressional wave velocity of 1500 m/sec, the approximate timing accuracy needed to locate the sources within 50 m is 0.035 sec. Because the stations are distributed on a plane, the timing accuracy must be even better, say 0.025 sec, to get

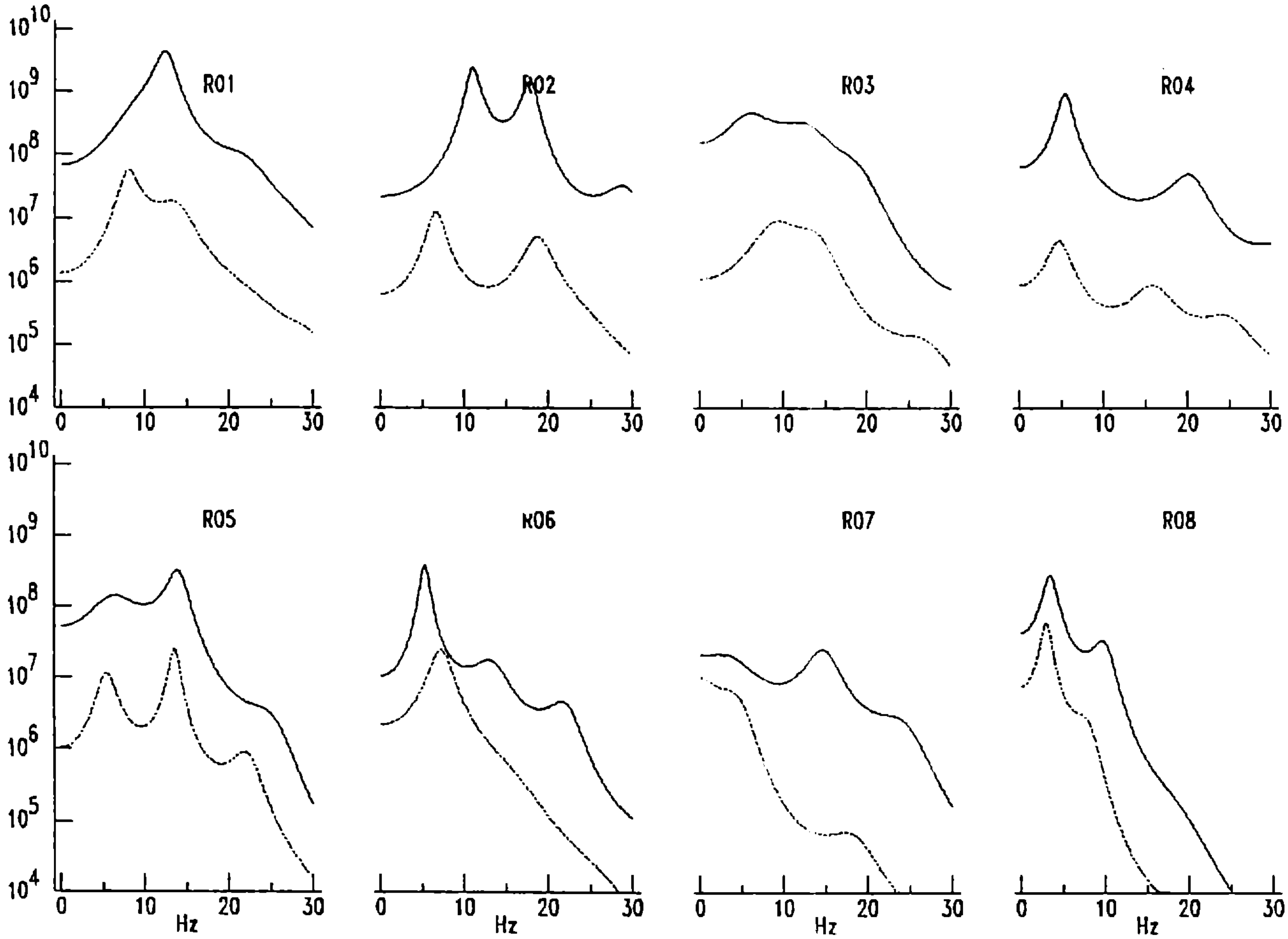

Figure 5. Power spectra for one-second segments of signal (solid) and noise (dotted) from another pre-collapse event.

depth accuracy of 50 m. A successful processing scheme based on arrival time locations must consistently time the phase arrivals to within 0.025 sec to be useful for our purposes. The criterion for evaluating other methods (besides arrival-time picking) will be that they give location resolution of 50 m.

Another requirement of our processing algorithm is that it must produce enough locations to tell us something significant about the activity and give a statistical stability to the location estimates. Ideally, a monitoring system would need to produce hundreds of locations to provide a reliable monitoring capability.

Picking first arrivals

Although several algorithms exist to determine the time for the initial onset of the P-wave at the individual stations, experience has shown that these algorithms cannot do better than the human eye. Efforts to make picks by hand were unsuccessful for the pre-collapse data because of the high background level and the emergent onsets of the arrivals.

Simultaneous Time and Frequency Domain Analysis

A signal processing technique that looks at power as a function of frequency and time was attempted. To get a preliminary idea whether the method would work, the event of Figure 3 was processed in this way, and plots were made of the time- frequency-power relationship for all eight traces (Figure 6). If the method were to be successful, the onsets of the direct phases would have to produce distinct and recognizable patterns that would allow high-resolution time picks to be made. Although on some traces patterns are apparent when the 'signal' arrives, they are not distinctive enough to provide the time resolution required.

Polarization Analysis

In an effort to enhance the intitial or direct parts of the signals relative to the scattered or background energy, polarization analysis using the three orthogonal components was attempted. This was based on the fact that direct P- and S-waves are rectilinearly polarized and surface waves (noise) are elliptically polarized. Polarization filtering takes advantage of this difference to isolate the direct phases. Although the method yielded some success, it was not consistent enough from station-to-station and event-to-event to solve the location problem. In other words, the direct phases could be extracted from the signals, but only with much tweaking of the parameters, which makes the method unsuitable for real-time processing.

Another application of polarization analysis is the fact that the energy partitioning between the three orthogonal components depends on the direction of the source relative to the receiver. The direction could conceivably be determined for each station, and a location calculated. This idea was unsuccessful because the parts of the wavetrain that exhibited the polarization could not be isolated.

Energy levels at the stations

For an array that is very close to the source area, the relative amount of power registered at the stations could be a sensitive measure of relative distance to the source, and hence location. If a window approximately the duration of the event were used, it was hoped that station effects would be minimized. The method was tested on some events following collapse for which arrival times could be picked and locations obtained. The locations from the station power levels did not agree well with the time pick locations. It appeared that near-station effects as well as the inhomogeneity created by the cavity were having too large an effect on the amount of energy reaching the stations. Although

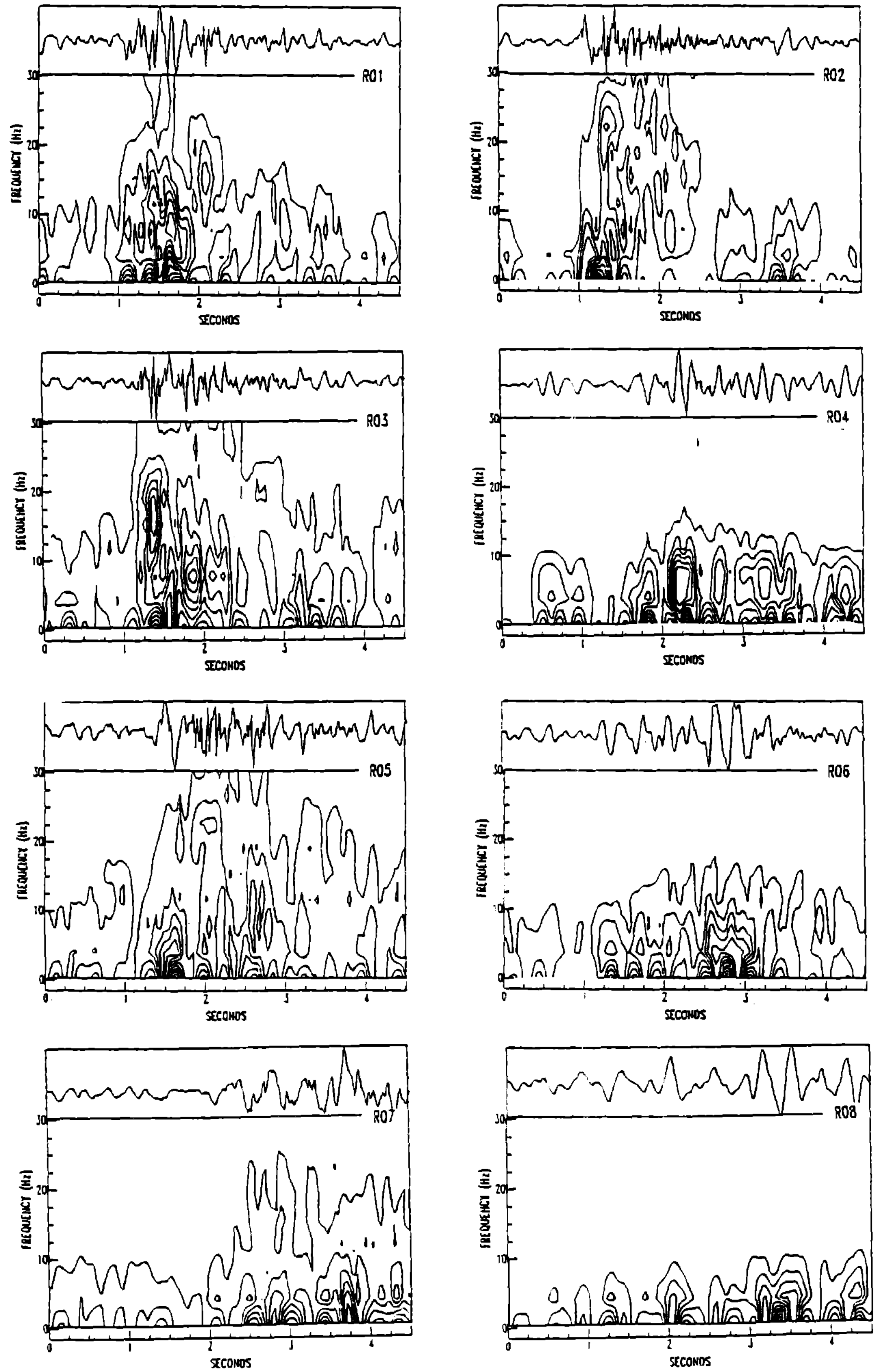

Figure 6. Contour plots of power as a function of time and frequency for a pre-collapse event. The time-series is at the top of each plot

it looked somewhat promising, the method would require careful calibration, which makes it impractical for our use.

RECOMMENDATIONS FOR FURTHER EXPERIMENTS

Although this study did not solve the problem that was originally being addressed, it greatly added to the knowledge of seismic signals generated by pre-collapse activity. With this knowledge, we are prepared to make some recommendations for future experiments that will have a much higher chance of success.

The major problem with the approach used for the EGMONT experiment is the difficulty in extracting the precise arrival times of direct phases for distinct events from the 'noisy' traces. More specifically, the problem lies in identifying the arrival of a common phase at each station that can be timed to the necessary precision. This problem is caused by the great differences in the traces at the individual stations. A possible solution using arrays is outlined next.

Arrays

An array, a set of closely spaced seismometers, can determine the directions of multiple sources at any instant in time. For instance, three crossed arrays consisting of about twelve vertical sensors each (see Figure 7) could be be used to independently estimate the directions (azimuth and angle of incidence) between the arrays and the seismic sources. Then, the three estimates of direction could be combined to determine the source locations.

Many algorithms exist for the processing of array data. In particular, the freqency-wavenumber method could be used to find the directions of propagation and the apparent velocities of the seismic wavefield. The velocity estimates could then be used to determine the depth of the sources. The array is well suited to estimating the location of sources that are closely spaced in time, which is an important consideration for our problem. In addition, estimates of source location can be obtained every few seconds with an array, so that hundreds of source locations can be obtained in a typical pre-collapse sequence.

In order to use arrays successfully several assumptions must be satisfied at least approximately. First, the array must be far enough from the sources that the signal impinging on the array is approximately a planewave (about 10 wavelengths). Second, over the analysis time window, over which a phase is segmented, the signal should exhibit temporal stationarity and spatial homogeneity (these two requirements are satisfied by most seismic signals). Finally, the array should be designed such that the signals are coherent and the noise incoherent among the seismometers. By comparing the scenarios of this problem to others which were successfully attacked and solved by arrays, it seems that the above assumptions are not unreasonable for this problem.

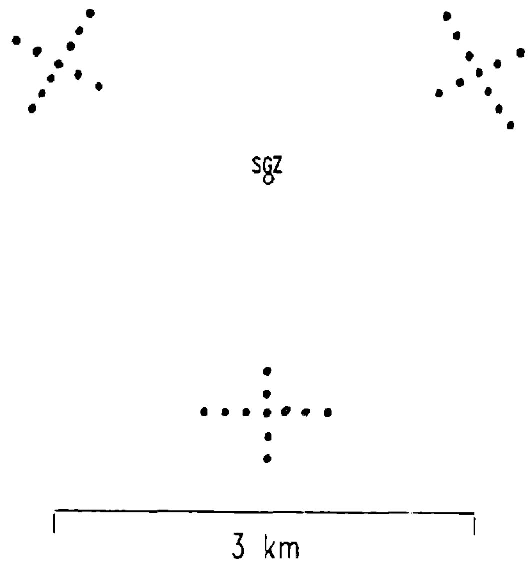

Figure 7. A possible arrangement of array sensors for the monitoring of pre-collapse activity

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